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Direct Torque Control of Permanent Magnet Synchronous Motor with Three Level Space Vector Modulation

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Abstract
In this paper, the performance of a permanent magnet synchronous control method motor and impact of the direct torque with three level space vector modulation presented. The proposed control method can reduce the flux linkage and torque ripple in a large extent and have a better dynamic and static performance. Space Vector Modulation (SVM) Technique has become the important PWM technique for three phase Voltage Source Inverters for the control of AC Induction, Brushless DC, Switched Reluctance and Permanent Magnet Synchronous Motors. The study of space vector modulation technique reveals that space vector modulation technique utilizes DC bus voltage more efficiently and generates less harmonic distortion when compared with Sinusoidal PWM (SPWM) technique. Both SPWM and SVM control strategies are implemented to obtain three level output voltages. In this work, DCMLIs for PMSM with DTC is carried out in MATAB/ Simulink/SimPower System environment. Comparative analysis is investigated for total harmonic distortion (THD) using both control strategies for three level with SVM and SPWM.

Keywords:PMSM, DTC, SPWM, SVM, MATLAB/SIMULINK.

Nomenclature

V_d	direct axis stator voltage, V
V_q	quadrature axis stator voltage, V
I_d	direct axis stator current, A
I_q	quadrature axis stator current, A
R_d	direct axis resistance, Ω
R_q	quadrature axis resistance, Ω
P	no. of poles
L_d	direct axis inductances, H
L_q	quadrature axis inductances, H
λ_d	direct axis flux linkage, wb
λ_q	quadrature axis flux linkage, wb
λ_f	magnetic flux linkage, wb
Ω_e	rotor speed in electrical, rpm
Ω_m	mechanical speed, rad/s
J	moment of inertia, kg.m^2
B	Viscous Friction Co-efficient, Nm/rad/s
P	Differential operator
T_e	electromagnetic torque, Nm
T_L	load torque, Nm

Acronyms

DCMLI	Diode Clamped Multi Level Inverter
PMSM	Permanent Magnet Synchronous Motor
DTC	Direct Torque Control
SVM	Space Vector Modulation
SPWM	Sinusoidal Pulse Width Modulation

1. Introduction
Permanent-Magnet Synchronous Machines (PMSMs) are used in the recent years due to their advantages over other ac motors such as high torque-to-current ratio, high power-to-weight ratio, high efficiency, high power factor, low noise, and robustness [1] [2]. PMSM Motor is made up of rare earth and neodymium boron magnets; it has been widely used in high performance variable speed industrial applications. In this motor, Permanent Magnets are placed in the rotor, because of absence of windings in the rotor, rotor copper losses are zero [3].PMSM applied in various industrial fields including aviation, rail traction, robotics, electrical vehicles, and servo applications [4][6][9]. Ideal flux circle generated by three-phase symmetric sinusoidal voltage, use the effective voltage vector generated by different switch patterns of inverter to approximate the standard flux circle [5] [6].Direct torque control (DTC) and field-oriented control (FOC) are the two most popular methods for high performance permanent-magnet synchronous motor (PMSM) drives. Lack of inner current controllers, rotary coordinate transformation, and pulse width modulation in DTC yields a faster dynamic response and a simpler structure in comparison with the FOC method. Although DTC method has the above advantages, it has some drawbacks among which the high torque and stator flux ripples are the most important, followed by variable switching frequency with respect to the motor speed and the load [7]. Compared with FOC, DTC can

manipulate stator flux vector directly so as to produce the desired torque [8]. A PI torque controller is introduced to calculate the voltage reference, which is implemented by the SVM [9] [10].

The paper is organized as follows: Section II revolves around the introduction of multilevel inverters. Section III explains control strategies SPWM and SVM. Section IV explains the modelling of PMSM. Section V focuses on the simulation results of a comparative analysis of THD, speed and torque responses of PMSM with SPWM and SVM and also with DTC technique. Section V summarises the conclusions drawn from the work with future recommendations.

2. Multilevel Inverters

The methods used for higher level inverter output voltage, the three methods are Connecting devices in series, using switching devices with higher voltage rating, or adopting multilevel topology. The first method can be used only when the problem of dynamic voltage sharing has been efficiently solved. Otherwise it should be avoided. The second method is complicated but compromise of the cost, reliability and availability. Given limited device voltage ratings, the most effective solution to higher inverter voltage is multilevel topologies. One of the multilevel structures that has much gives preference and widely used is the Neutral-Point-Clamped multilevel inverter or also known as Diode Clamped multilevel inverter. This structure was first proposed in 1980 . Basically, NPC multilevel inverters synthesize the small step of staircase output voltage from several levels of DC capacitor voltages. An m-level NPC inverter consists of (m-1) capacitors on the DC bus, 2(m-1) switching devices per phase and 2(m-2) clamping diodes per phase. The DC bus voltage is split into 3 levels by using 2 DC capacitors. Each capacitor has input DC voltage across the capacitor in volts and each voltage stress will be limited to one capacitor level through clamping diodes. The number of levels can be extended to a higher level by additional switching devices and with these additions, the inverter will be able to achieve higher AC voltage, producing more voltage steps that will be approaching sinusoidal with minimum harmonics distortion. During inverter operations, the switches near the centre tap are switched on for a longer period compared to the switches further away from the centre tap. As the switch is further away from the centre tap the switching time is shorter. Another difference between the conventional 2-level and multilevel NPC is the clamping diode. In case of 3-level NPC inverter, clamping diode, four clamped diodes having the DC bus voltage into three voltage level, +Vdc/2, 0 and - Vdc/2. A multilevel converter has several advantages over a conventional two-level converter that uses high switching frequency pulse width modulation (PWM). The attractive features of multilevel inverters can be briefly summarized as follows: i). MLIs produces output voltage with less distortion, dv/dt stresses hence reduces electromagnetic problems. ii). It generates small common mode voltage so that the stress in the bearings of a motor reduces to a significant extent. Also this common mode voltage can be eliminated by adopting advanced modulation strategies. iii). It draws input current with low distortion factor iv). Operation with both fundamental switching frequency and high switching frequency gives less switching loss and higher efficiency.

3. Control Strategies

Modulation techniques and control strategies have been developed for multilevel converters such as sinusoidal pulse width modulation (SPWM), selective harmonic elimination (SHE-PWM), space vector modulation (SVM), and others. The proposed DCPMIs are developed three level with SPWM and SVM. The proposed DCPMIs are developed up to nine levels with SPWM and SVM.

Space Vector Modulation

The control strategy, space vector modulation gives fast dynamic response and wide linear range of fundamental voltage compared with the conventional pulse width modulation techniques. The proposed work is based on SVM for multilevel inverter. The SVPWM for multilevel inverters involves mapping of the outer sectors to an inner sub-hexagon sector, will be very complex, as a large number of sectors and inverter vectors are involved. Conventional space vector PWM (SVPWM) is a widely used PWM strategy which has the advantages of low harmonic distortion in the output current and suitable for digital implementation. In SVPWM technique, actual switching times can be produced by the recombination of effective voltage vectors using the information of the reference voltage vectors location. The flowchart for three level SVM DCMLI is depicted in figure 2.

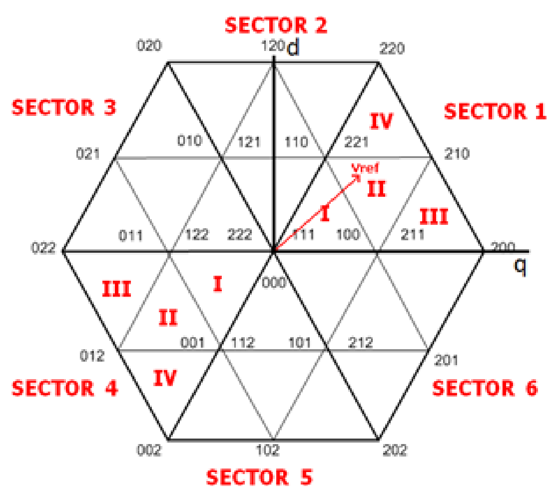

Figure1. Space vector hexagon for three level SVM

4. Direct Torque Control of PMSM

The control methods used for the permanent magnet synchronous motors are: V/f control, field oriented control and direct torque control. Direct Torque control is one of the control methods of the PMSM. In the proposed work, direct torque control of PMSM with three level space

vector modulation is considered. In this work PMSM is modeled in MATLAB/SIMULINK environment. Modeling equations for PMSM are given in equations (1) to (8). The proposed block diagram of the work is given in figure 2.

$$V_d = R_d\, i_d - \omega_r\, \Psi_q + \frac{d\Psi_d}{dt} \quad (1)$$

$$V_q = R_q\, i_q + \omega_r\, \Psi_d + \frac{d\Psi_q}{dt} \quad (2)$$

$$\Psi_d = L_d i_d + \Psi_{af} \quad (3)$$

$$\Psi_q = L_q i_q \quad (4)$$

Where all voltages (v) and currents (i) refer to the rotor reference frame. The subscripts q_s, d_s, q_r and d_r correspond to q and d axis quantities for the stator(s) and rotor(r) in all combinations, R_a denotes the armature resistance, I_{qs} denotes quadrature axis inductance, I_{ds} denotes direct axis inductance etc.

Then the flux linkages are written as

$$\Psi_d = L_d i_d + \Psi_{af} \quad (5)$$
$$\Psi_q = L_q i_q \quad (6)$$

Where Lm is the mutual inductance of the stator winding and rotor magnets.

The developed torque motor is being given by

$$T_e = \frac{3}{2} P(\Psi_d i_d - \Psi_q i_q) \quad (7)$$

The mechanical Torque Te written in eq.

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \quad (8)$$

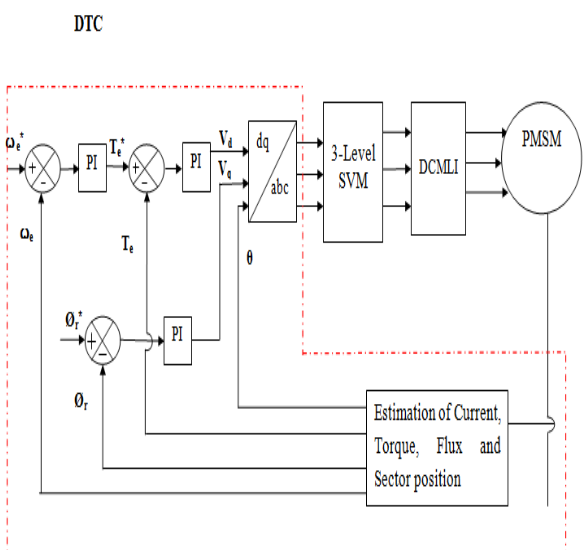

Figure.2. Proposed block diagram

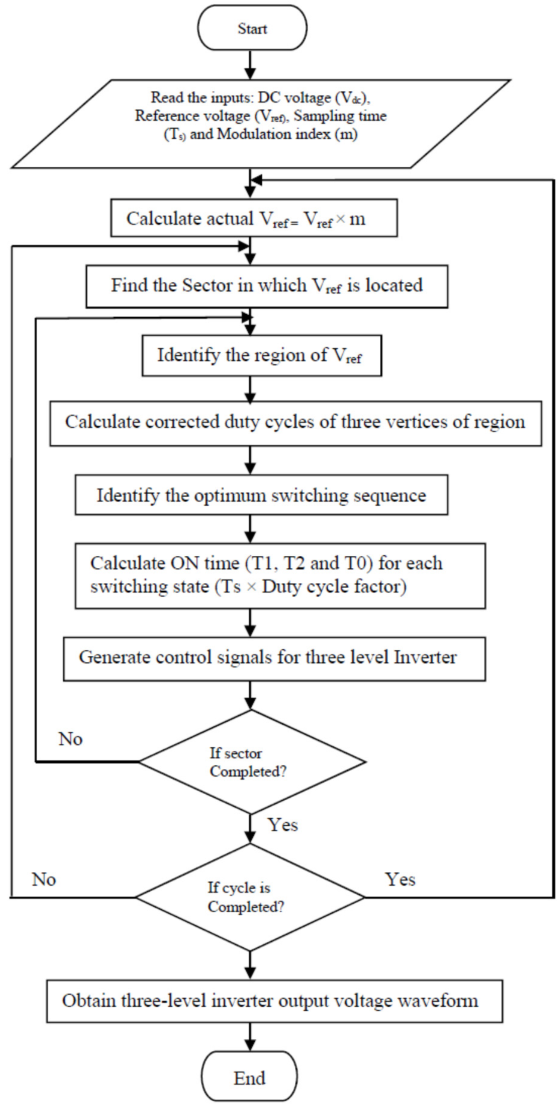

Figure3. The flow chart for three level SVM

5. Results and Discussion

The dynamic performance of direct torque control permanent magnet synchronous motor using three level space vector control is carried out using MATLAB/Simulink.

There are three test cases; at first the analysis of Three Level DCI Fed PMSM is carried out Using SPWM. In second case the simulation is carried out for the Three Level DCI Fed PMSM Using SVM. Finally the dynamic analysis is carried out for DTC of PMSM with three level SVM. The results are plotted from figure 4 to figure 6. In all three cases the load torque 10Nm is applied at t=1 sec. In the case of DTC with SVM gives better results with reduced harmonics, torque ripples and steady state error also got reduced to low value.

The results depict that as the level of phase voltage increases the THD decreases for phase voltage and currents, also the torque ripples reduces, which is clearly shown from figure 4 with SPWM, from figure 5 with SVM and from figure 6 with DTC with three level space

Vector modulation. In these three cases DTC with SVM gives better results with reduced harmonics, torque ripples and steady state error also got reduced to low value. The THD analysis is given in Table 1. It is very well clear that THD for phase voltage reduces from 37.61% to 3.77% and current reduces from 4.27% to 2.53% respectively. The results have been presented and analyzed in this paper. The parameters of the PMSM and dc voltage considered for this paper is presented in Table 2.

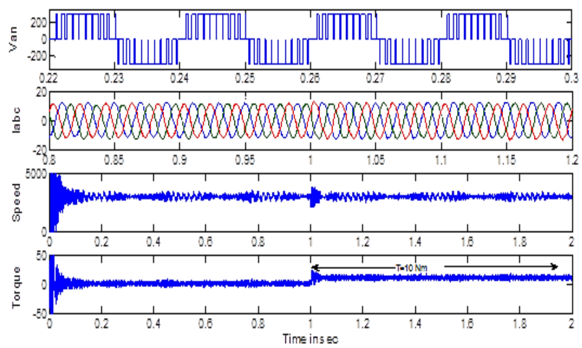

Figure 4. Three Level DCI Fed PMSM Using SPWM when load torque 10 Nm applied at t=1 sec

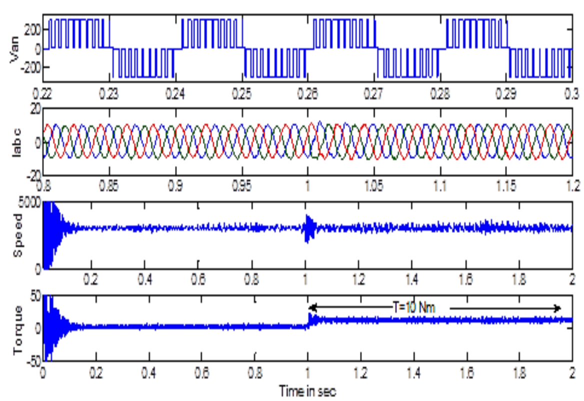

Figure 5. Three Level DCI Fed PMSM Using SVM when load torque 10 Nm applied at t=1 sec

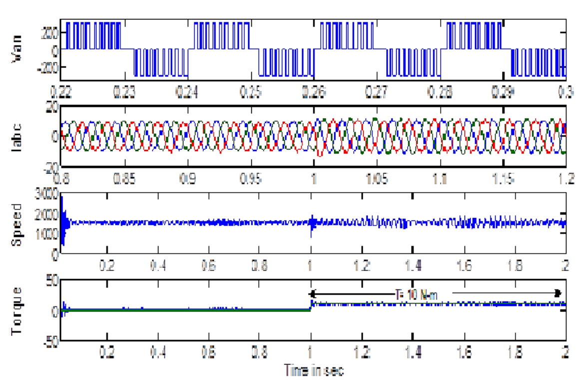

Figure 6. Three Level DCI Fed PMSM with DTC Using SVM when load torque 10 Nm applied at t=1 sec

Table 1.THD Analysis for 3 Level Inverter fed PMSM

S. No	V_{THD}	I_{THD}
	SPWM	
1	37.61%	4.27%
	SVM	
2	3.77%	3.05%
	DTC-SVM	
3	3.77%	2.53%

Table2. PMSM Parameters

Parameter	Description Value
Stator Resistance	2.875 Ω
Direct Axis Inductance	0.0085 H
Quadrature Axis Inductance	0.0085 H
Moment of Inertia	$0.0008 Kgm^2$
Friction Vicious Gain	0 Nm/rad/s
Number of Poles	8
DC Voltage	600 V

6. Conclusion

The inverter output voltage is proportional to the number of active switches and the gate signals generation with SVM gives low harmonic distortion, in the this paper three level with SPWM and SVM is implemented for DTC of PMSM. A direct torque control of PMSM is introduced in this paper. By using SVM, the dynamic and static performance of the control system is better performance DTC of PMSM. Simulation results indicate that the proposed SVM-DTC can reduce the flux and torque ripple efficiently. It is further suggested that the proposed work further can be implemented with fuzzy logic and model reference adaptive control techniques.

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Biographies

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